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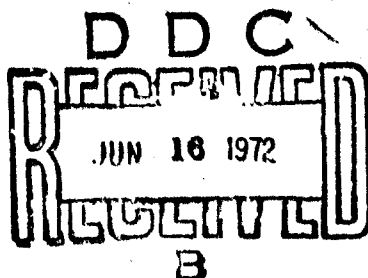
GLASS REINFORCED PLASTIC SANDWICH STRUCTURE TEST
PRELIMINARY RESULTS

by
John Bader

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STRUCTURES DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

April 1972



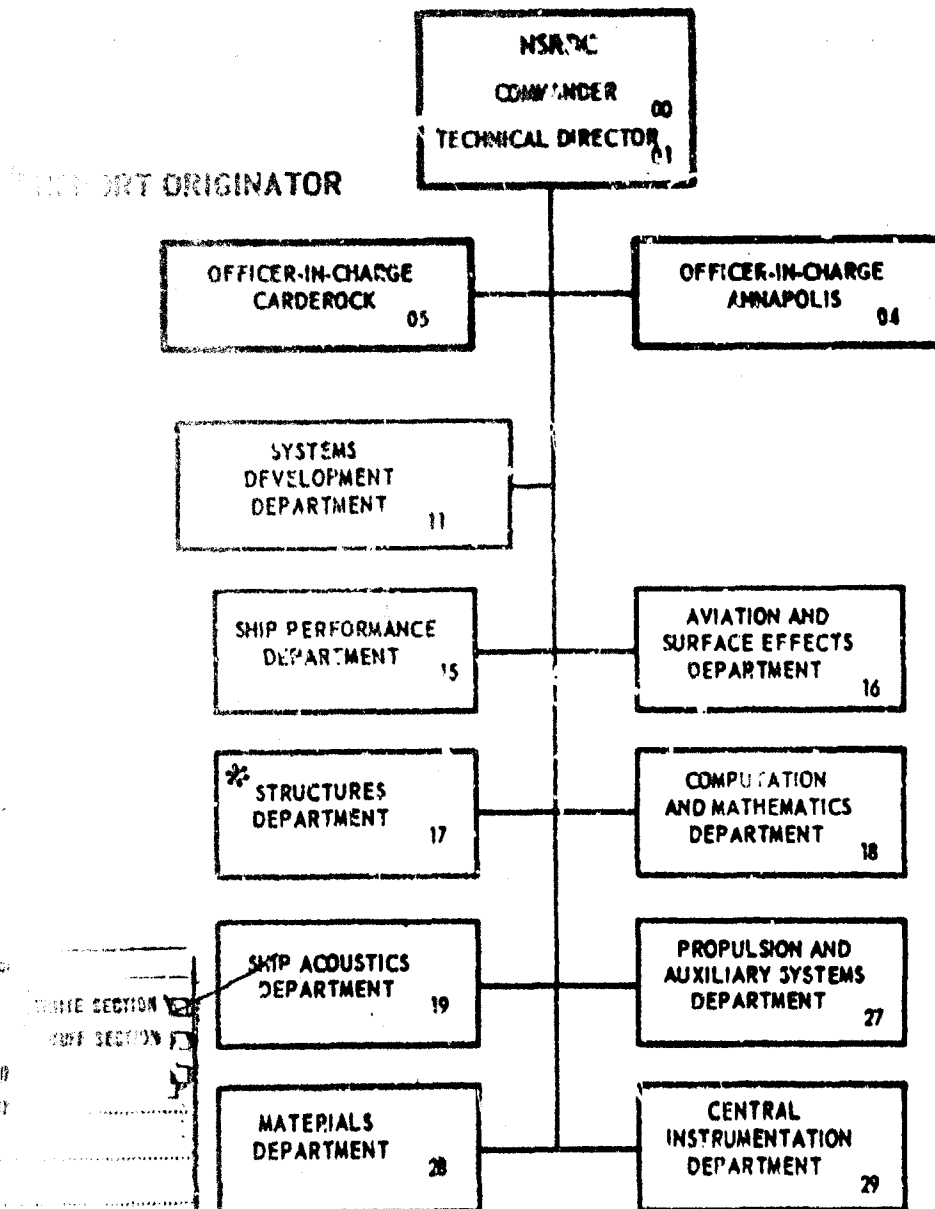
Report 3834

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Details of illustrations in
this document may be better
studied on microfiche

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TABLE OF CONTENTS

	Page
ABSTRACT	1
ADMINISTRATIVE INFORMATION	1
ACKNOWLEDGMENTS	1
INTRODUCTION	1
BACKGROUND	4
ARRANGEMENT	5
TEST FIXTURE AND INSTRUMENTATION	15
PANEL INSTRUMENTATION AND TEST PROCEDURE	17
TEST RESULTS	22
ANALYSIS OF TEST RESULTS	28
CONCLUSION	36

LIST OF FIGURES

	Page
Figure 1 - Test Panel with Bolt Holes	3
Figure 2 - Examples of Stiffener Designs	6
Figure 3 - General Arrangement of the Test Panels	9
Figure 4 - Details of the Sandwich Construction for Panels 1, 2, and 3	10
Figure 5 - Automatic Layup Machine	11
Figure 6 - Cross Sections of Two Stiffener Designs	13
Figure 7 - Details of Stiffener for Panels 1 and 2	14
Figure 8 - Details of Stiffener for Panel 3	14
Figure 9 - Modification to Top Skin Edge Thickness of Panel 1	16
Figure 10 - Modification of Stiffener Skin Thickness of Panel 2	16
Figure 11 - Test Fixture for the Full-Scale Stiffened Panels	18
Figure 12 - Panel Loading Equipment	19
Figure 13 - Panel and Stiffener Instrumented with Recording Gages	20

	Page
Figure 14 - Measured Deflections for Panel 1	23
Figure 15 - Measured Deflections for Panel 3	23
Figure 16 - Maximum Measured Strain for Panel 1	24
Figure 17 - Maximum Measured Strain for Panel 2	24
Figure 18 - Maximum Measured Strain for Panel 3	25
Figure 19 - Strain on Stiffeners of Panels 1 and 2	26
Figure 20 - Strain on Stiffeners of Panel 3	26
Figure 21 - Deflection Measured at the Center, Panels 1 and 2	30
Figure 22 - Comparison of Measured and Predicted Deflections for Panel 1	30
Figure 23 - Comparison of Predicted Stress and Measured Strain on Panel 1	32
Figure 24 - Comparison of Predicted Stress and Measured Strain on Panel 2	32
Figure 25 - Measured Strain on Stiffeners versus Neutral Axis Location	34
Figure 26 - Strain along the Top of the Stiffener, Modified Panel 2	35

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ABSTRACT

The preliminary results of a joint industry-government research project are described for static tests of a fixed-edge, stiffened boat structure of glass-reinforced plastic (GRP) sandwich construction. The measured stresses and deflections are compared with predictions of panel response. Since the physical properties of material in the panels will not be available until completion of the proposed test program, comparison of test results was based on typical values for reinforcing and core materials. The agreement between test data and the values predicted by using a finite-element approximation of test panel structure were encouraging and indicate that the analytical method holds promise as a tool for rational design of GRP boat structures.

ADMINISTRATIVE INFORMATION

Five sandwich glass-reinforced plastic test panels were constructed by private companies using proprietary methods and at no cost to the U.S. Government. The project was initiated with in-house funding but has been supported to a major extent by funds from the U.S. Amphibious Assault Landing Craft program, NSRDC Code 118.

ACKNOWLEDGMENTS

The author acknowledges the assistance provided by Mr. Paul P. Day (Code 178) in constructing test fixtures and Mr. Frederick S. Koehler (Code 178) in conducting tests. This program would not have been possible without the valuable aid from the two companies who assisted in the design and furnished the test panels. Finally, the author thanks Mr. Melvin W. Brown of Code 118 for the funding support provided to this date.

INTRODUCTION

Early U.S. Navy experience during the development of glass-reinforced plastic (GRP) material for boat hulls indicated that the sandwich arrangement had serious limitations.¹ Since then, however, there has been

1. Spaulding, K.B., Jr., "A History of the Construction of Fiberglass Boats for the Navy," Bureau of Ships Journal, Vol. 15, No. 3 (Mar 1966).

progress in the development of new GRP sandwich materials and improved construction methods. Furthermore, in its recommendations on design practice for GRP sandwich structures,² the Navy noted a need for more data on performance. This exploratory program was undertaken to develop better procedures for GRP material selection and boat sandwich structure design. The initial truss core test panels were selected as one arrangement which could overcome previous objections to GRP sandwich structures.^{1,2}

A GRP sandwich structure consists of outer layers of glass (cloth, roving, or random-oriented fiber reinforcement) separated by core materials such as low density foams, balsa wood, and honeycombs of paper, GRP, or aluminum. The truss core for the test panels of this study consisted of GRP webs secured to the outer skins and foam-filled spaces between the truss webs. This truss core serves to transmit loads to support and stabilize the skin against premature buckling. Two types of construction were investigated. Unicore, Inc. furnished four panels and Aerojet General Corporation constructed one panel to dimensions to suit the loading test fixture and suggested reinforcing materials. These sandwich structures were not intended to be optimum but rather were intended to demonstrate the effects of reinforcing designs for sandwich arrangements. Other arrangements, such as honeycomb in place of the truss core, need to be evaluated in a similar manner in order to develop a design method.

The "Unicore"^{*} stitched truss core sandwich can be arranged to the required truss spacing, truss thickness, and core configuration. The Aerojet General Corporation designed sandwich panel with prefabricated core and skin fabrication technique may provide the construction method to ensure laminated quality and resin glass ratio for optimum strength in construction. The drilling of bolt holes for clamping the panels in fixtures and the instrumentation were accomplished at the Naval Ship Research and Development Center (NSRDC). Figure 1 shows the drill used for the mounting holes and a panel with holes ready to be instrumented.

2. "Strength of Glass-Reinforced Plastic Structural Members," Parts 1 and 2 Design Data Sheet 9110-0 (8 Jun 1969).

^{*}Trade name for material by Unicore, Inc.

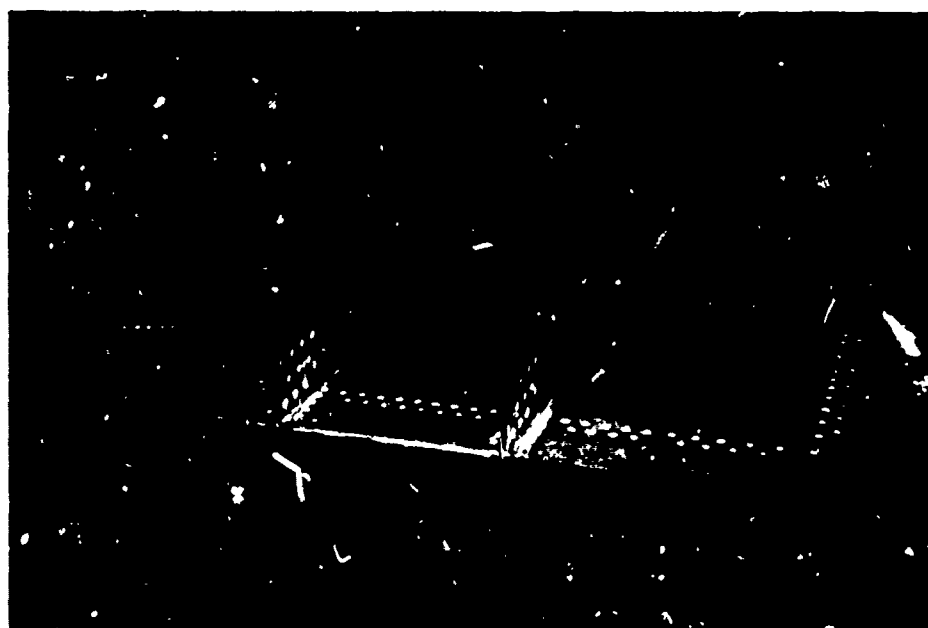


Figure 1 - Test Panel with Bolt Holes

This test report is divided into discussions of the need for better design information (background), the arrangement of test panels and stiffeners, test programs, test results, analysis of results, and conclusions. The test results and analysis are qualitative only since the panels were not loaded to failure. The continuation of this program for dynamic (impulse) load tests, fatigue tests, and tests of other sandwich designs, including material properties, is subject to adequate funding support.

BACKGROUND

Prior to 1970, the Bureau of Ships of the U.S. Navy devoted considerable effort to the development of design data for the application of GRP to boat and ship hull structures. These efforts led to several design summaries and were helpful in converting the structure of most hulls of U.S. Navy boats to GRP material. The initial experimental craft with sandwich hulls were constructed by using a low-cost paper honeycomb or a foam which reacted with chemicals in the polyester resin formula. The paper honeycomb in the boat hull dissolved after a period of use, and the reinforcing skin on foam core hulls separated from the foam when foam was crushed by hull impacts. Both conditions caused such unacceptable losses in structural strength that the boats were in danger of becoming "water-logged."

In their study on GRP minesweeper hulls Gibbs & Cox, Inc. rejected the sandwich construction in favor of a single-skin GRP hull because of limited sandwich thicknesses and other out-dated considerations. The Navy summary evaluation of GRP for a minesweeper hull³ noted these limitations and dismissed sandwich structures from further consideration. As a result, hulls of high performance craft have been constructed of aluminum, even though the sandwich construction has been found the optimum arrangement in many areas of aircraft design.

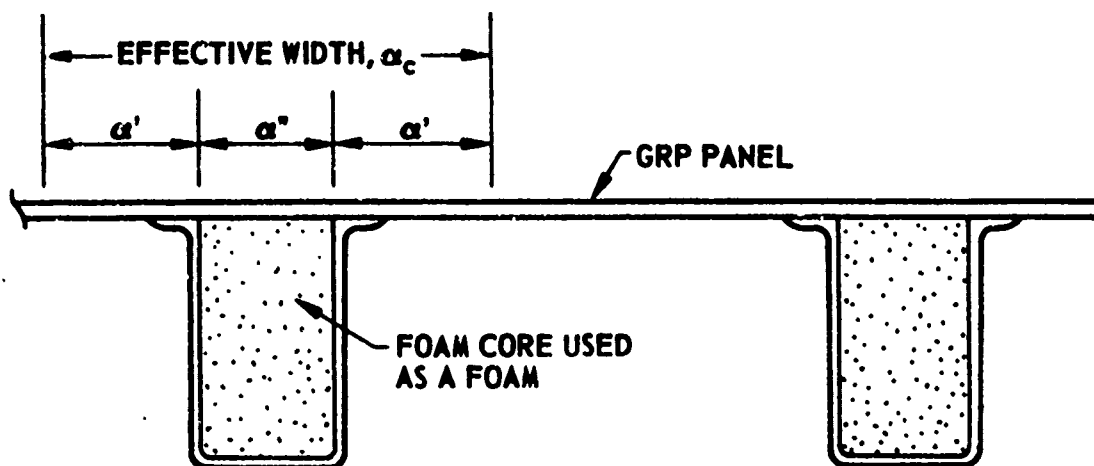
3. Fioriti, L. et al., "Evaluation of Glass Reinforced Plastics for Surface Ships," Naval Ship Engineering Center (Jul 1966).

The Navy design development for application of GRP culminated in Design Data Sheet (DDS) 9110-9 which established methods to be used for U.S. Navy ship or boat designs. An excerpt from that DDS is included here under the heading "Limitations for Design." This excerpt notes a lack of adequate clamped panel and orthotropic material property data. To a great extent, this GRP "design data" sheet is copied from aircraft practices which use extremely thin skins and for which in-plane load, buckling (stability) is the controlling failure consideration. Furthermore, note from the excerpt that the design methods do not include the fixed-edge conditions that are of primary concern in boat structural design. Figure 2 (reproduced from the DDS) shows examples for the design of stiffeners. The data are inadequate for selecting dimensions. Criteria need to be given to permit the choice of proper height, width, flange dimensions, and skin thickness and to determine the effect of the panel on stiffener strength. The illustration of the "HI-HAT" stiffener shown in Figure 2 is not discussed in the DDS except for a (debatable) definition of the effective width (without further justifications). These descriptions are considered inadequate and the faying flange shown for the "HI-HAT" stiffener entirely unsuitable and too small for adequate bonding to the hull skin. The "beam" design shown in the lower portion of Figure 2 is actually a distorted version of the usual panel plate-strip strength check for a unit width of plating. This "beam" designation could be misleading to novices who may wish to use the DDS to develop a GRP structural arrangement.

ARRANGEMENT

Arrangement possibilities for GRP sandwich structures are infinite; in addition to the core, they include orientation and type of reinforcement, combinations of reinforcement, and thickness of reinforcement versus thickness of sandwich. The GRP sandwich test panel arrangements described here are only a few of the many promising candidates for ship or boat structures. For example, a new improved water-resistant paper honeycomb core with very high impact resistance is available in addition to a NOMEX*

*DuPont company designation for proprietary material.



TYPICAL HI-HAT STIFFENER-PANEL COMBINATION

WIDTH OF BEAM = 6 INCHES

COMPOSITION: TOP 1/3 OF BEAM IS WOVEN ROVING;

$$E_f = 1.7 \times 10^6 \text{ p.s.i.}$$

MIDDLE 1/3 OF BEAM IS RANDOM MAT;

$$E_f = 0.86 \times 10^6 \text{ p.s.i.}$$

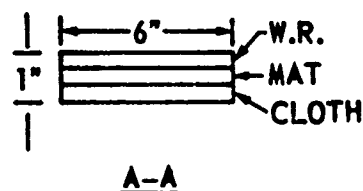
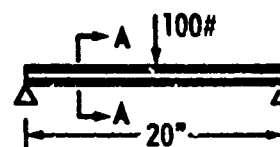
BOTTOM 1/3 OF BEAM IS GLASS CLOTH;

$$E_f = 1.9 \times 10^6 \text{ p.s.i.}$$

DETERMINE: DEFLECTION OF THE BEAM

COMPUTATION:

$$\text{COMPOSITE } E_f = \frac{1}{l} \sum_{i=1}^{i=n} E_i l_i$$



FORMULAS FOR STIFFENERS SUPPORTING SANDWICH PANELS AND COMBINED STRESSES AS GIVEN IN PART I OF THIS DDS ARE APPLICABLE TO SANDWICH PANELS.

NOTE: TAKEN FROM DDS 9110-9 "STRENGTH GLASS REINFORCED PLASTIC STRUCTURAL MEMBERS"

Figure 2 - Examples of Stiffener Designs

LIMITATIONS FOR DESIGN
(Excerpt from DDS 9110-9, Part II)

Critical shear buckling

Formulas given for compression buckling apply also to shear buckling except for coefficients K_M and K_{MO} use Figures 18 to 23.

On the figures note that $K_{MO} = K_M$ for $V = 0$.

Curves for clamped sandwich panels with orthotropic cores are approximate because they were obtained by multiplying buckling coefficients for simply supported orthotropic sandwich by the ratio of clamped to simply supported buckling coefficients for isotropic sandwich.

The curves given are applicable to the same α , β , and γ values noted for compression buckling. For isotropic facings it was assumed that $\mu = 0.25$. For orthotropic facings it was assumed that $\mu_{ab} = \mu_{ba} = 0.2$, $E_{Fa} = E_{Fb}$, and $G_{Fba} = 0.21 E_{Fa}$.

If the figures do not apply because of large variances in the properties assumed, the formulas given in reference (d) can be used.

9110-9-1 Rectangular flat sandwich panels under uniform normal loading

Detailed procedures giving theoretical formulas and graphs for determining dimensions of the facings and core for resisting bending from normal loads for simply supported panels are given in the following paragraphs. Double formulas are given, one formula for sandwich with isotropic facings of different materials and thicknesses and another formula for sandwich with each isotropic facing of the same material and thickness. Facing moduli of elasticity, $E_{F1,2}$, and stress values, $F_{F1,2}$, shall be compression or tension. Data for clamped edge panels are not presently available.

The following formulas are for determining sandwich facing and core thicknesses and core shear modulus so that chosen design facing stresses and allowable panel deflections will not be exceeded. The facing stresses, produced by bending moment, are maximum at the center of a simply supported panel under uniformly distributed normal load. If restraint exists at panel edges, a redistribution of stresses may cause higher stresses near panel edges. The procedures given apply only to panels with simply supported edges. Because facing stresses are caused by bending moment, they depend not only upon facing thickness but also upon the distance the facings are spaced, hence core thickness. Panel stiffness, hence deflection, is also dependent upon facing and core thickness.

special high strength nylon honeycomb material. A comparative evaluation should be carried out for a solid balsa core and a single-skin GRP.

The dimensions and the general arrangement of the test panels are shown in Figure 3. The panel size was selected to permit approximately full-scale structural tests of fixed-edge, stiffened panels. The 30 in. stiffener spacing compares with 31 in. for the 50-ft aluminum hull patrol craft (PCF). The test panel width was selected to obtain a minimum value of 2 for the panel side ratio. Side panels were made wider than center panels in an effort to minimize the edge-fixidity effect on stiffener torsion forces. Core insets, truss web spacing, and sandwich thickness were selected to evaluate the effects of shear transfer and local "hard spots" at the supports of the panel. Plywood inserts were specified along panel edges to minimize crushing when the panel is clamped in the test frame.

The details of reinforcement for the three panels tested are shown on Figure 4. Panels 1 and 2 were furnished by Unicore, Inc. and incorporate a patented, stitched core-skin construction. Panel 1 has an equilateral truss arrangement and one layer of woven roving (plus a surface layer) for the skin. Panel 2 has a square core and two layers of woven roving reinforcement. The direction of the warp of cloth and truss core is at right angles to the stiffeners for both Panels 1 and 2. The type of cloth and number of layers are shown on Figure 4. The truss core acts to carry shear loads to the panel supports and to stabilize the skin, thus overcoming the major objections cited earlier. Balsa wood core insets (10 in. wide) in place of foam core were located under the stiffeners to minimize "hard spots" and to reduce the otherwise high bending stress at a fixed support.

The arrangement of the truss core for Panel 3 is shown in Figure 4. This panel was fabricated by a special patented Aerojet General automatic layup machine (Figure 5) which accurately controlled the resin-glass content of glass reinforcement and provided optimum strength. The truss core members with extra layers under stiffeners and ends were fabricated separately and secondarily bonded to skin. (This method for automatic skin layup would be more suitable for a honeycomb core.) The face reinforcement consists of an 18-in. shingle layup with 3-in. laps as shown on the figure.

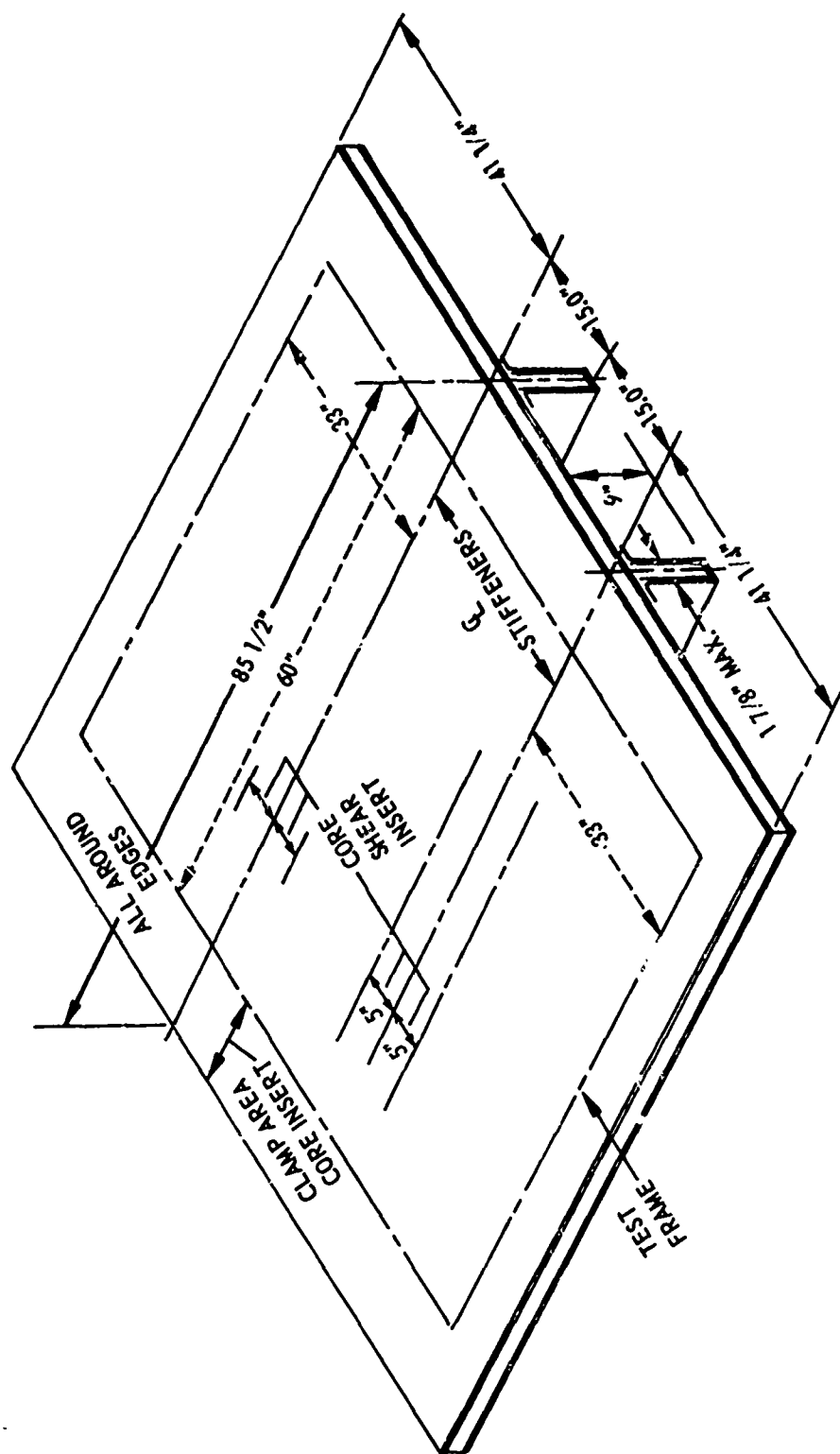


Figure 3 - General Arrangement of the Test Panels

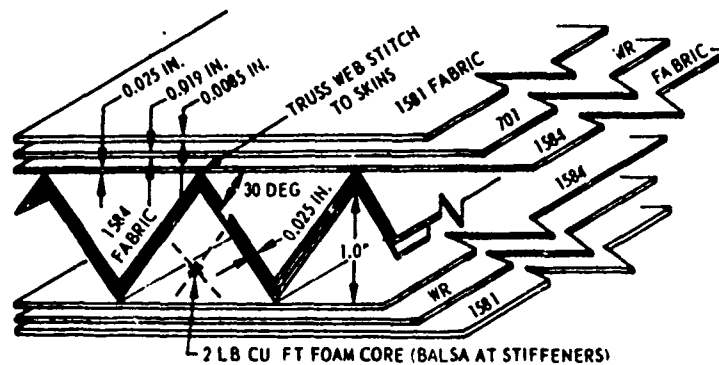


Figure 4a - Panel 1
(Information furnished by Unicore, Inc.)

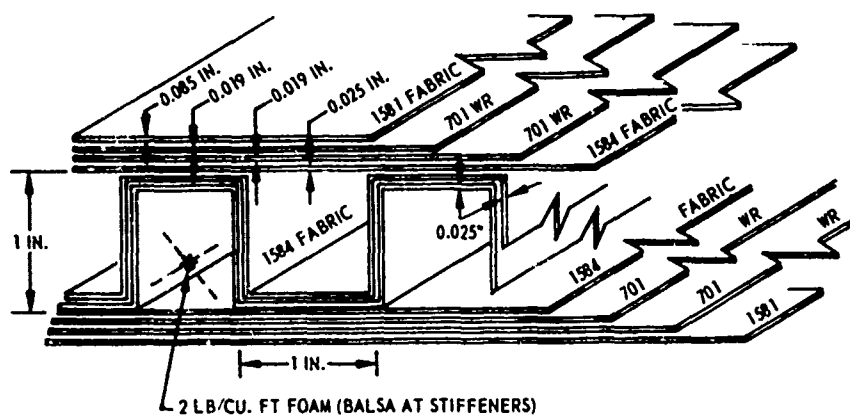
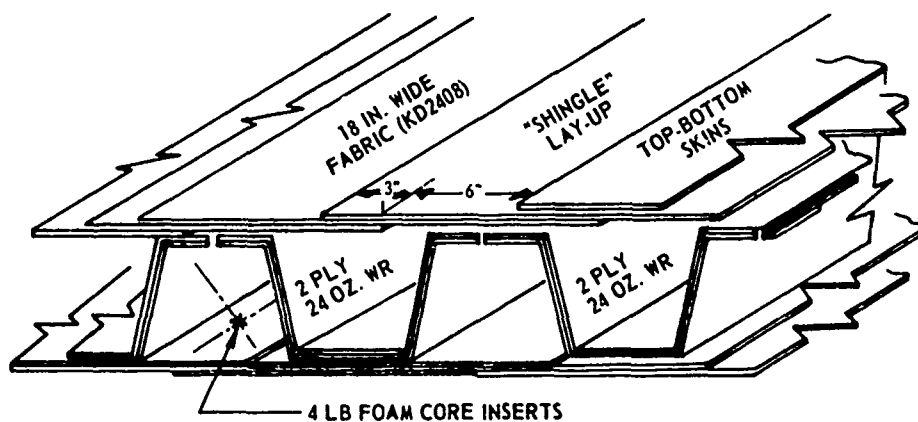


Figure 4b - Panel 2



NOTE: 2 ADDITIONAL PLY WEBS AT STIFFENERS
(10 IN. LONG)
SKIN-TRUSS WEBS SECONDARY BONDED

Figure 4c - Panel 3
(Information furnished by Aerojet General Corporation)

Figure 4 - Details of the Sandwich Construction for
Panels 1, 2, and 3

(No scale)



Figure 5 - Automatic Layout Machine
(Photograph courtesy of Aerojet General Corporation)

The actual skin thickness has not yet been determined. The analysis of test results will not be possible until sections can be made of the panel to determine the material properties and thickness.

The dimensions and reinforcement of panel stiffeners were determined to meet test requirements. Figure 6 shows the cross sections of two stiffeners. Figure 6a is the shape suggested by Gibbs and Cox⁴ and Figure 6b that selected for the test panels. The Gibbs and Cox modified, wider, "HAT" cross section shape was proposed for a single-skin GRP minesweeper hull. This stiffener has an adequate flange width, but the wide web spacing and relatively shallow depth are not considered satisfactory. The wide spacing permits the skin to deflect between stiffener sides (web) and has a greater slope at the stiffener flange, thus increasing the peeling force action of the flange. The shallow depth reduces the effective shear area of the stiffener and possibly affects inertia adversely. The stiffener proportions for the test panel shown in the lower part of the figure were intentionally made narrow and deep to reduce the effects on panel response and to better measure the panel-stiffener interaction.

Construction details of the stiffeners on Panels 1 and 2 are shown in Figure 7. A 9-inch height was chosen to provide a suitable bolting area for clamping the ends. This stiffener depth permitted better measurements of strain slope at the center of the stiffener span for evaluation of neutral axis location. The thickness of the stiffener skin for Panels 1 and 2 (approximately 1/16 in.) was selected to explore the possible buckling action of thin skins. Skin thickness was increased for Panel 3 (Figure 8) to ensure that the stiffener would not fail before the panel failed. The actual thickness of the skin and stiffener for Panel 3 will have to be determined when it can be cut apart. Stiffeners on Panels 1 and 3 were secondarily bonded to sandwich skins without mechanical fasteners.

The 2 1/4-ft-wide (approximate) stiffener flanges of Panels 1 and 2 are a continuation of the reinforcing layers of the stiffener skin. The

4. Gibbs and Cox, Inc., "Marine Design Manual for Fiberglass Reinforced Plastics," McGraw-Hill Book Company, Inc. (1960).

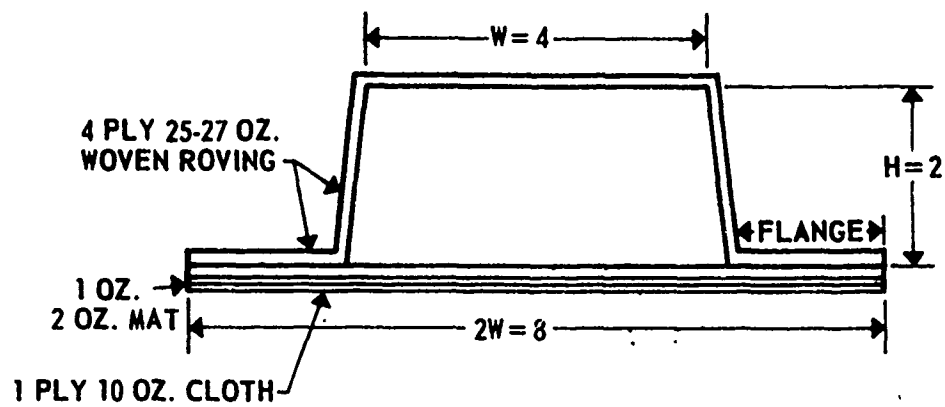


Figure 6a - Gibbs and Cox Design Example 6-20
(See pages 6-75 of Reference 4)

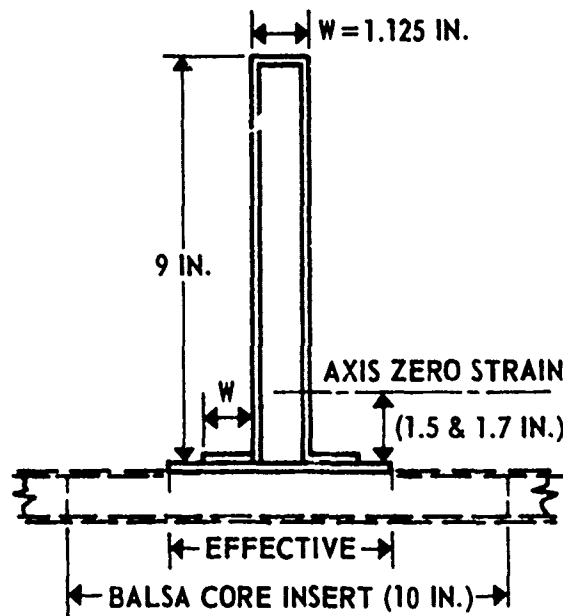


Figure 6b - Beam Selected for the Test Panels

Figure 6 - Cross Sections of Two Stiffener Designs

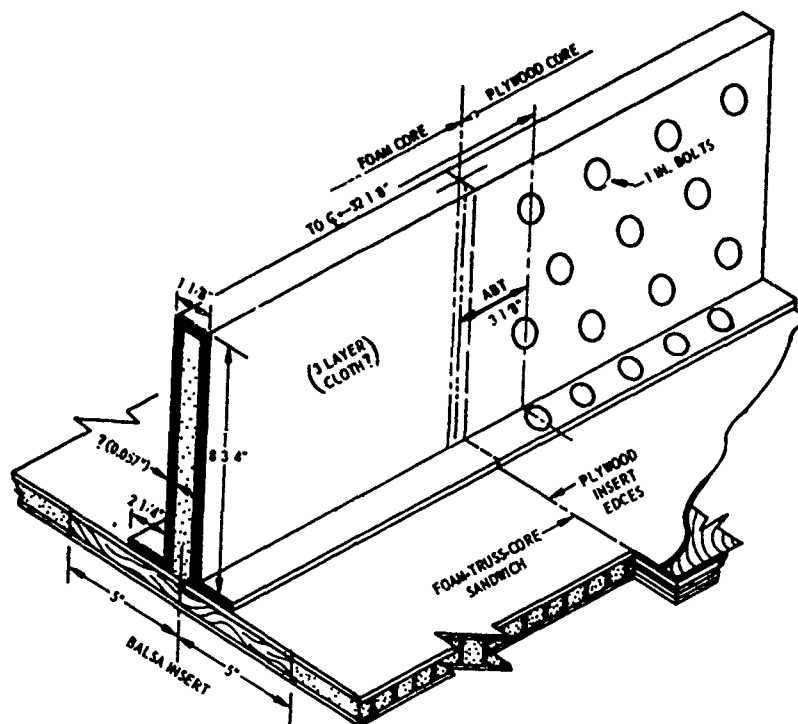


Figure 7 - Details of Stiffener for Panels 1 and 2

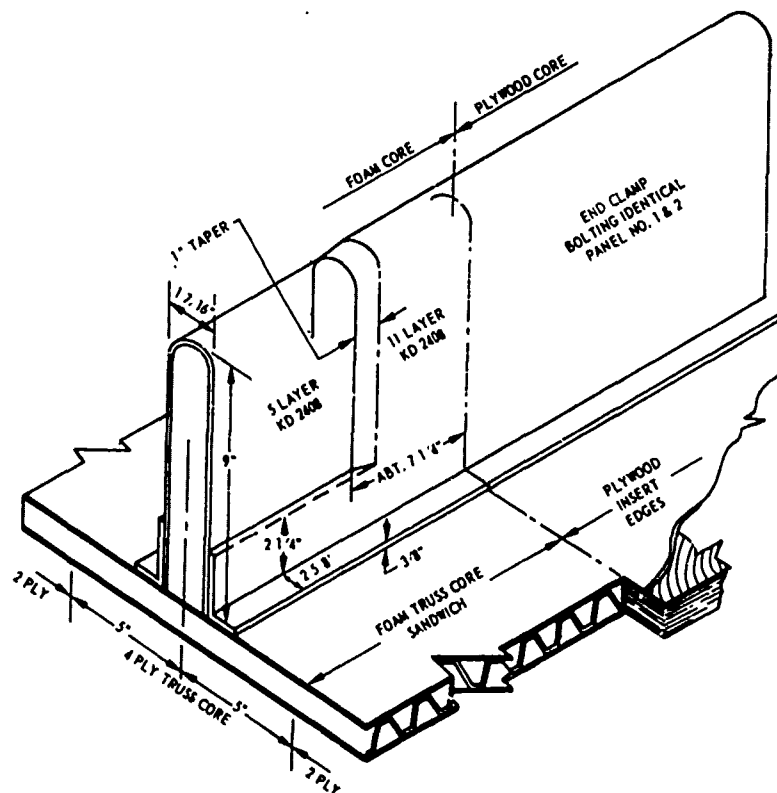


Figure 8 - Details of Stiffener for Panel 3

The flanges of stiffeners on Panel 3 were formed by using additional layers bonded to the stiffener and to the panel. These flanges are approximately 3/8 in. thick. No mechanical fasteners were used so that it would be possible to observe the response of the secondarily bonded stiffener connection under impulsive loading. In actual practice, this flange should be tapered to reduce the stress discontinuity at the edge. The stiffeners on Panel 3 also incorporated additional layers of reinforcement at the ends to provide added strength for the larger bending moment at the fixed ends.

The initial tests of Panels 1 and 2 demonstrated the need for additional reinforcing of sandwich and stiffener at "built-in" edges. Panel 1 was modified by the addition of layers of cloth along the edges as shown in Figure 9. The number of "doubler" layers was chosen to ensure that strains would be reduced by 50 percent with allowance for loss in strength due to the secondary bond. Figure 10 shows similar reinforcing on the stiffeners of Panel 2. Since provisions had been made for the increased loading at the "built-in" part of Panel 3, no modification was necessary on this "design" up to the 15-psi maximum static load used.

TEST FIXTURE AND INSTRUMENTATION

A review of published literature failed to disclose any description of a suitable fixed-edge stiffened panel test. A discussion of 5 x 7-ft "clamped" panels is available,⁵ but it does not indicate whether the edges were "fixed."

The fixed-edge requirement is difficult to achieve since the actual clamping action on the structure to be tested depends on suitable methods of securing it for both edge bending and in-plane forces. It would be relatively simple to fix the edges of a panel without stiffeners. The fixed-edge condition could possibly be met for metallic materials by massive clamping devices or welded end attachments. However, in the case of the GRP structure, a special new loading fixture had to be designed to accomplish this objective.

5. Spalding, K.B., Jr. and R.J. Della Rocca, "Fiberglass-Reinforced Plastic Minesweepers," Transactions Society of Naval Architects and Marine Engineers (1965).

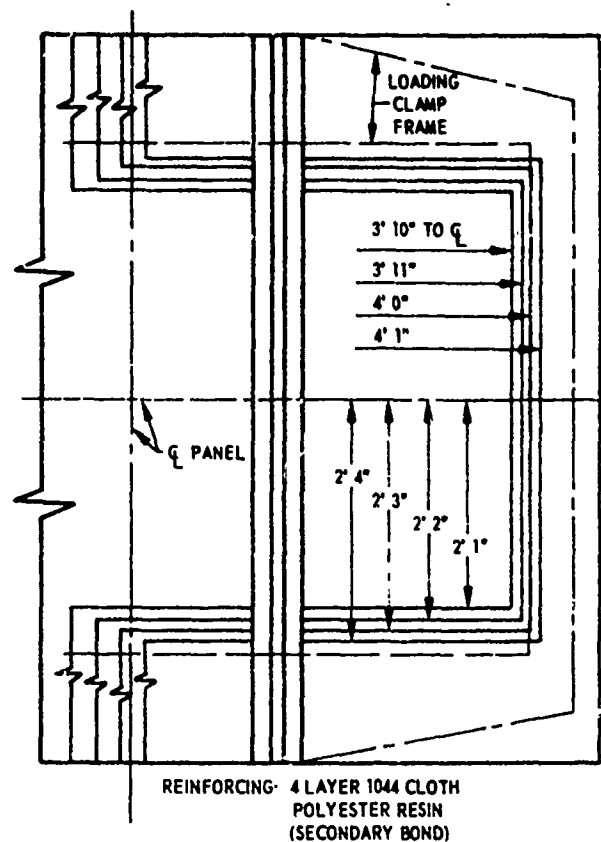


Figure 9 - Modification to Top Skin Edge Thickness of Panel 1

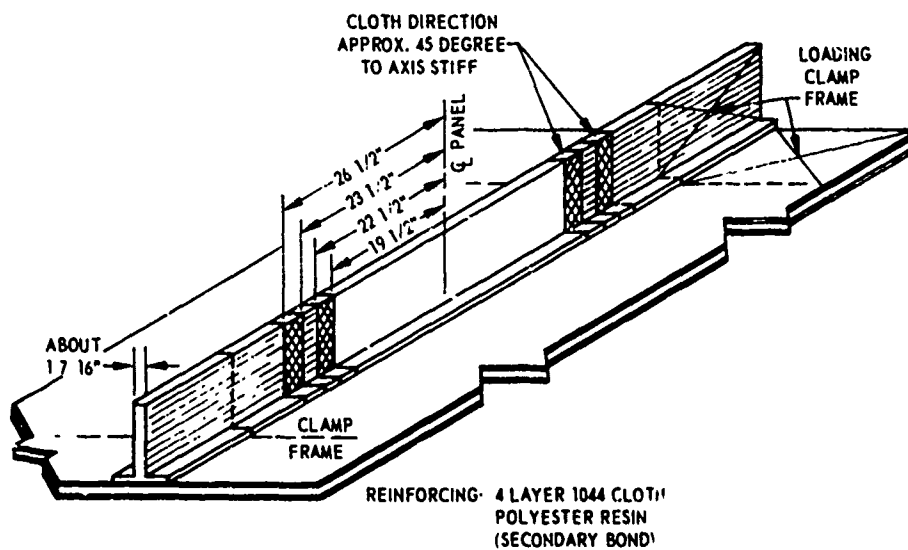


Figure 10 - Modification of Stiffener Skin Thickness of Panel 2

The test fixture for the full-scale stiffened panel is shown in Figure 11. There is a heavy steel lower pressure tank with an inlet and a drain connection for pressurizing water. The top flange of the pressure tank has tapped holes to receive the special high strength bolts used to secure the test panel with an upper clamp frame. This upper clamp frame was designed to fit on top of the stiffened test panel and to clamp the panel and ends of stiffeners on the panel under test rigidly around the edges. Panel edge fixidity is obtained by the clamping friction on the panel and by the shear and compression at the bolts in the panel skin and the plywood around the edges of the panels. In all, 94 bolts ranging in diameter from 5/8 to 1 in. are used along the edges of the panel; 20 bolts are located at the ends of each stiffener side and flanges. Each panel is prepared by drilling the mounting holes, and is clamped on the loading frame by a top clamp fixture. The bolts are torqued hand-tight, and plywood inserts are located at the sides of the stiffeners and the clamp frame for additional clamping action.

The hydrostatic pressure in the lower tank part is regulated by an electric booster pump and monitored on dial gages, a pressure transducer, and a mercury manometer located in the water return line from the pressure tank. Surplus water is stored in an outside tank connected to the system through a transfer pump. This equipment is shown in Figure 12. Loads up to 100 psi can be applied, although panel tests are expected to require considerably less than one-half of this pressure. The maximum pressure is limited by the size of the clamping bolts.

PANEL INSTRUMENTATION AND TEST PROCEDURE

Strain and deflection gages were installed along the test panel and stiffener centerlines and edges (see Figure 13) to evaluate the sandwich panel response to the uniform normal loading and to check the critical design features. These consisted of 37 single-element and 14 three-element rosette strain gages and 12 linear potentiometer deflection gages. The strain gages were located at the top and bottom surfaces of the panel centerlines to determine possible membrane action (the sandwich cross section is symmetrical about its center). The three-element rosette gages



Figure 11 - Test Fixture for the Full-Scale Stiffened Panels

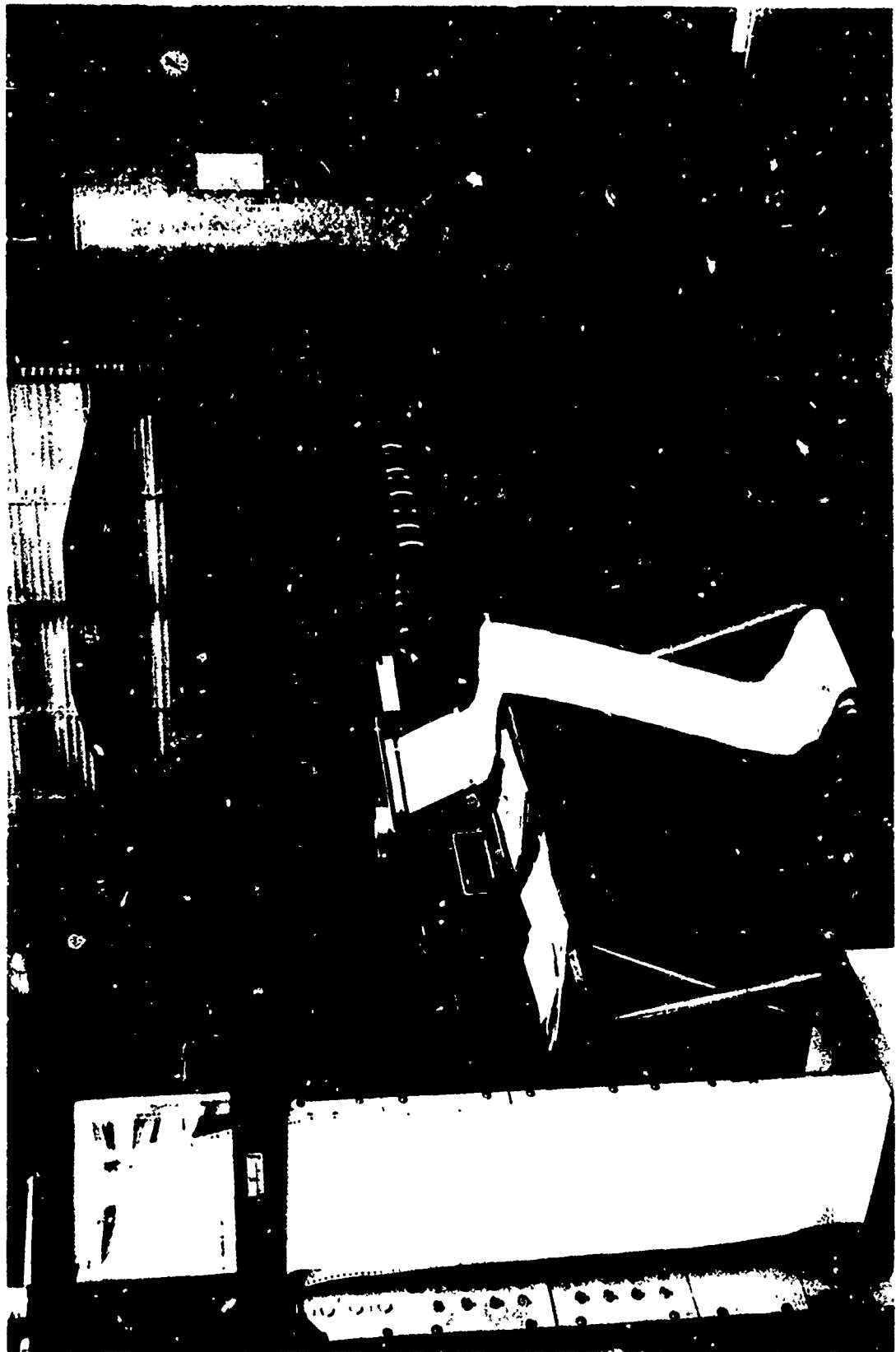


Figure 12 - Panel Loading Equipment



Figure 13 - Panel and Stiffener Instrumented with Recording Gages

were placed along the side of the stiffener to determine the direction of principal stress and to check for the location of the stiffener neutral axis. The deflection measurements were taken to provide data on the stiffness of sandwich arrangement and to check the predictions obtained from a finite element analysis. One deflection gage was located to measure changes in relative distance between the tops of the stiffeners at the center of the panel and to indicate the stiffener torsion action.

The panel strain response was recorded on a 96-channel Gilmore recorder (see Figure 12). Deflections of the center of a panel and one stiffener were also continuously monitored on a Hewlett Packard recorder. The strain gages were connected to the Gilmore recorder through two switch boxes, and the deflection gages have a balancing unit for zero adjustment. Deflections were tabulated manually.

The test procedure consisted of establishing zero hydrostatic pressure at the test fixture and setting zero values for the instruments. Hydrostatic pressure was then increased in 1-psi increments.

Panel 1 was loaded to 6 psi, Panel 2 to 9 1/2 psi, and Panel 3 to 15 psi. Modified Panels 1 and 2 were tested to 10 psi. The maximum loading for the test panels was selected to show possible elastic buckling but without actual failure so that retesting could be carried out later under proposed "dynamic" load conditions.

Care was taken to ensure proper identification of each gage with location on the panel and on the recording device. The hydrostatic pressure was observed as inches of mercury in the manometer, and the value was corrected for the difference (24 1/2 in.) in level between the top of the test fixture and the manometer.

A check was carried out to determine whether the deflection and strain values could be duplicated. In every case, the second set of values was close to the values observed initially except for data in areas of buckling action. Moreover, where response was not linear with increasing panel load, the strain records returned to a slightly different "zero" value. At most locations, the largest variation from linearity was near maximum and minimum load and indicated a possible minor variation in edge fixidity. Some difficulty was experienced with the calibration of the pressure transducer located at the pressure tank outlet connection (this instrument was "borrowed" from another project).

TEST RESULTS

The test results are presented in typical plots of deflections and strains for the three panels. However, these values do not indicate the erratic recordings of gages which were located in areas of compression instability at the edge of Panel 1 or in areas of shear instability on the side of stiffener ends adjacent to the test frames for Panel 2. The erratic response at these locations did not appear to be useful except to indicate incipient instability. The somewhat uneven (wavy) top surface of Panel 1 resulted in buckling along the edge parallel to the truss core at the clamp frame. The sides of the fixed ends of stiffeners for Panel 2 showed the start of shear buckling at a panel load of about 6.5 psi and an extreme deflection (about 1/2-in. dishing of sides and twist of stiffener) at 9.5-psi load, at which time the stiffeners had a large cant toward the center of the panel. As noted earlier, both of these panels were modified and subsequently retested.

The measured deflections of Panel 1 (panel and stiffener) are shown on the panel centerline (Figure 14) for the initial test to 6 psi and at the same load on the second test after reinforcement had been added along the panel edges. Deflection values from the second test are noted on the figure below those for the initial test. The deflections at the centerline of Panel 3 are shown on Figure 15 for maximum (15 psi) load; values at the 6-psi panel load are included for comparison with Panel 1 values.

The strain values shown for the three panels in Figures 16, 17, and 18 are for the same loadings as used for deflection measurements. The actual recorded strain values have been noted at each point on these figures. Strains were measured along the two centerlines on a panel (in one quadrant) and along the flanges of one stiffener. The strains along one flange at the side of the stiffener have been indicated separately (on the second stiffener) for clarity. An attempt to plot the slopes of all strain measurements had to be discarded because of the confusing overlap of various slopes. Measured strain data for stiffeners are shown in Figures 19 and 20.

The Panel 1 stations shown on Figure 16 are for the equilateral triangle core sandwich. The measured strain at the panel center was about

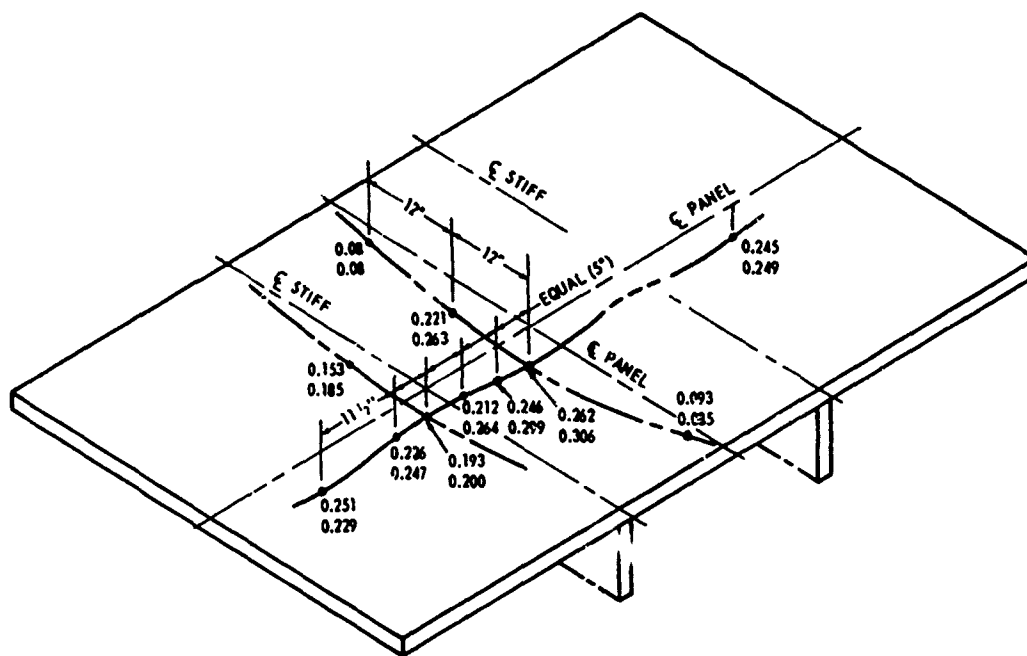


Figure 14 - Measured Deflections for Panel 1

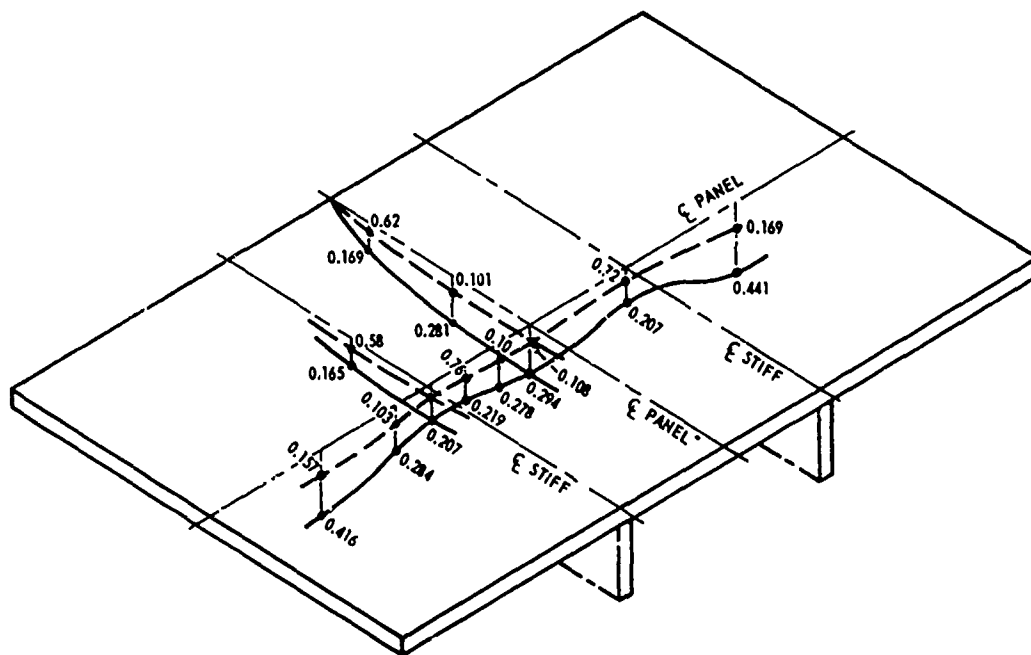


Figure 15 - Measured Deflections for Panel 3

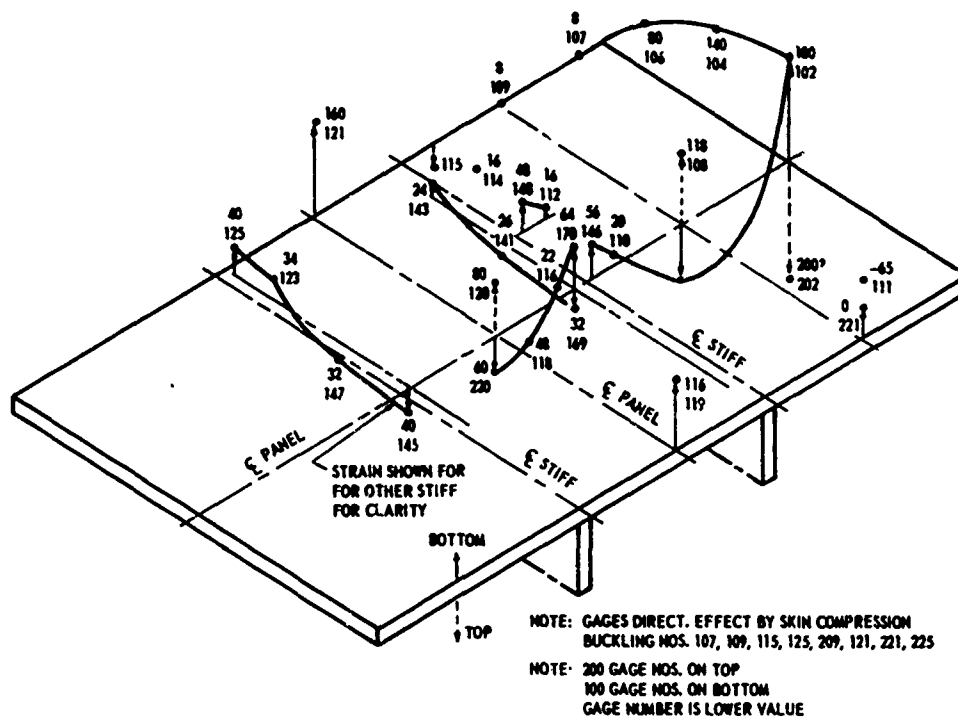


Figure 16 - Maximum Measured Strain for Panel 1

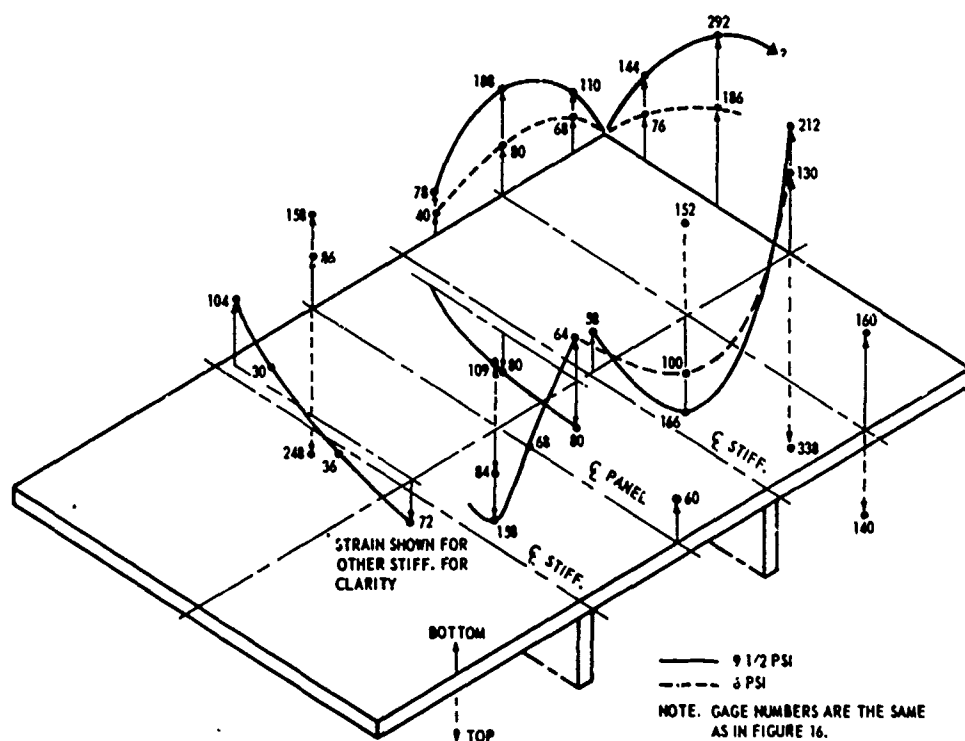


Figure 17 - Maximum Measured Strain for Panel 2

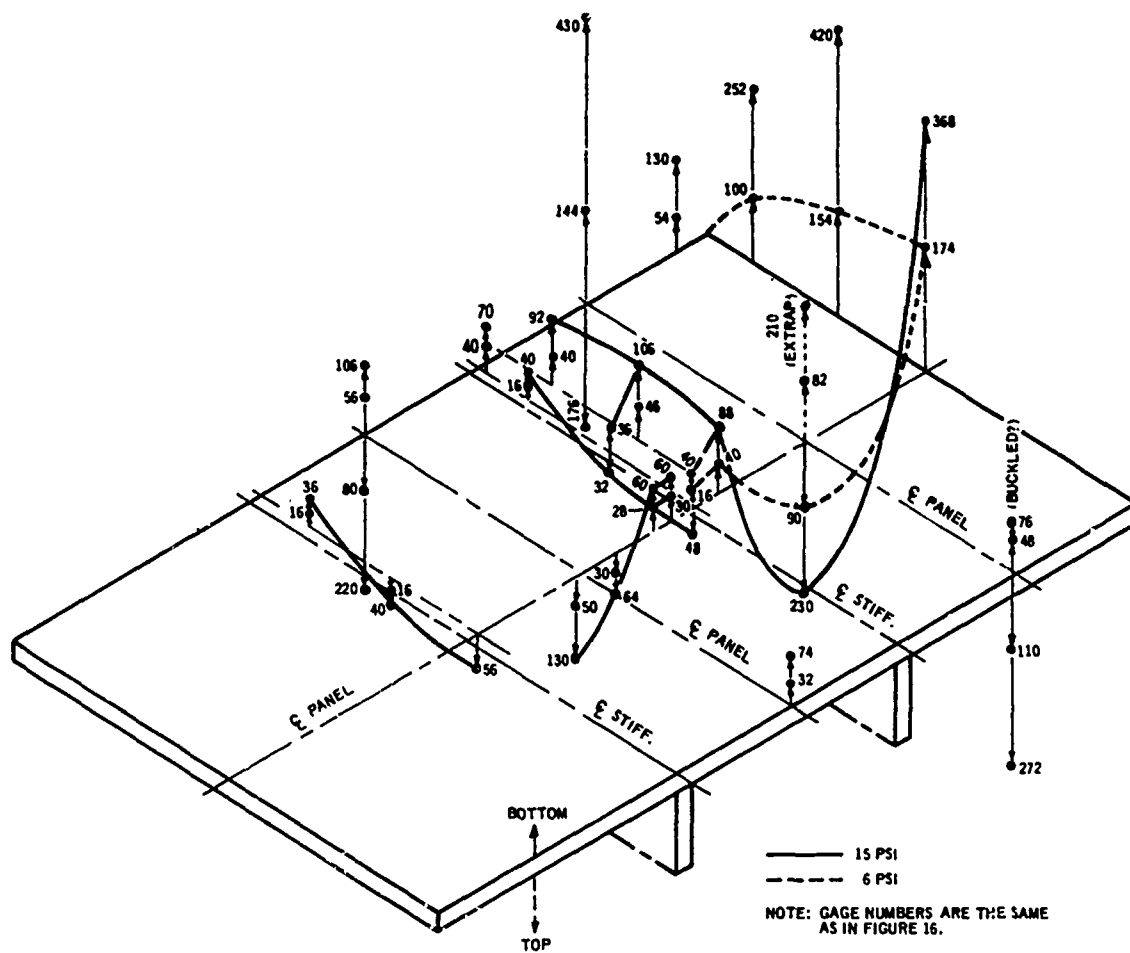


Figure 18 - Maximum Measured Strain for Panel 3

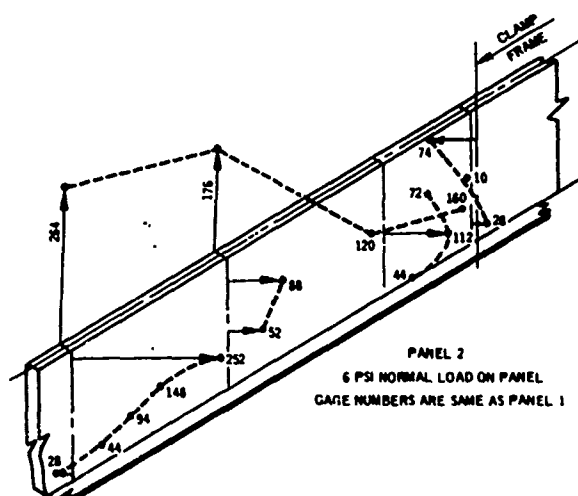
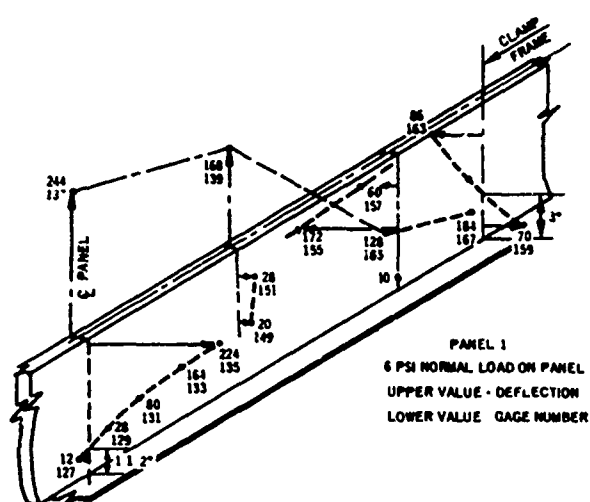


Figure 19 - Strain on Stiffeners of Panels 1 and 2
(Strain is given in $\mu\text{in/in}$)

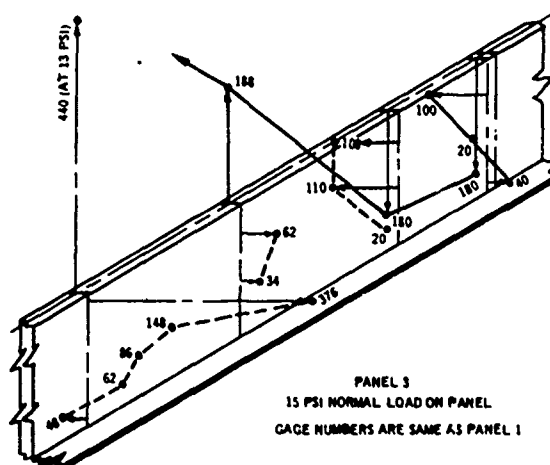


Figure 20 - Strain on Stiffeners of Panel 3

one-half that at the edge, as expected. However, the strains at the stiffener were reduced because of stiffener deflection and the increased local sandwich section modulus. The tensile strain (60 μ in./in.) at the center of the center panel was considerably less than the compressive value (80 μ in./in.) measured on the opposite face and less than that for the wider side panels. The strain distribution along the edge of the panel parallel to the stiffener seems reasonable.

The Panel 2 strains shown on Figure 19 are for the vertical truss core arrangement with an extra layer of woven reinforcement in the skins. Strains are shown along the panel centerline, the edges, and the stiffener flanges. Above the 6-psi loading, the strains were influenced by gradual shear buckling at the ends of both stiffeners. The added reinforcing layer for the second test eliminated the buckling along the edge perpendicular to the stiffeners. However, the strain distribution along the edge parallel to the stiffener has a larger value (Gage 104) than at the centerline (Gage 102); this was contrary to theoretical expectations of panel stress at the center of the fixed edge. The much larger tensile strain (Gage 202) would indicate possible edge fixidity or core failure. The relatively greater center panel strain (versus side panel centerline) at the maximum load was probably due to the stiffener shear buckling noted earlier.

Typical Panel 3 strains (Figure 20) were similar to those for the first two panels. The extra thick stiffener flange resulted in an appreciable reduction of panel strain at the stiffener. No skin buckling was observed to explain the very large difference between the edge strain of the center and side panels (Gages 121 and 109). The lower stress on the center of the long edge compared to adjacent location (Gages 102 and 104) is unexplained also. The large variation in strain at opposite edges of the side panel (Gages 144 and 111) indicates the possibility that uniform fixed edge support may not have existed.

The panel stiffener strains measured on the side and top of the stiffener (Figures 19 and 20) were obtained to check stiffener end fixidity, and shear distribution and to determine the effective neutral axis of the panel-stiffener arrangement. However, shear buckling at supports resulted in very erratic values for gages near ends of stiffeners, especially for

Panel 2. The strain records along the top of the stiffener depart from the expected ratio of a fixed end beam having an end moment (strain) equal to twice that at the center. The stiffener may have rotated to some extent at the clamped end, and the actual length may be between the location of the first clamping bolts for holding stiffener ends. The arrays of single element gages at the stiffener (panel) center show a reasonable pattern of strain; the cross-over points for the stiffeners are noted on the sketches. Unfortunately, the maximum strains of the stiffener, Panel 3, were beyond the range set for the Gilmore recording instrument. These stiffener strains would be influenced by torsion force on the stiffener.

ANALYSIS OF TEST RESULTS

Only a preliminary analysis of results is possible since actual material properties are not available. It was not possible to investigate internal changes or failures which could have occurred and influenced the recorded strain and deflections. However, some general observations on performance and design criteria are possible. Assumptions of typical material properties were also made to check a finite element procedure developed for predicting deflections and stress distribution.

The thin uneven upper skin (stiffener side) surface of Panel 1 showed buckling (compressive) along the fixed edge parallel to the truss core where the clamp frame edge was located between truss webs. The fixed ends of the stiffeners of Panel 2 experienced shear buckling, although similar stiffeners on Panel 1 had no noticeable distortion up to the 10-psi maximum panel loading. The secondary bonded additional local reinforcing on Panel 2 noted earlier prevented this behavior. However, at the maximum 10-psi load, the bond of the secondary bonded doublers on the panel between stiffeners failed on one side with a loud "pop." Because these panel modifications had been made by NSRDC mechanics experienced in GRP fabrication, no report had been requested on the method of preparing the surface for these changes. In future work, more funds will have to be allocated for greater quality control of the fabrication and changes to test models.

Figure 21 shows a representative relationship between deflection versus panel load for Panels 1 and 2 at the center of each middle panel. The dotted line connects the points of the first tests, and the solid line indicates measured values after the panels had been modified as noted previously. The slope of deflection versus load plots are curved at the beginning but become linear after panels are loaded. The curvature could be due to possible panel slippage at clamping bolts (bolts have a 1/16 in. clearance in the clamp frame) or to difficulty in defining an absolute zero load condition. The majority of the recorded strain slopes were essentially straight for the full range. However, gages located in areas of buckling were never linear as already indicated.

For a given span and sandwich thickness, the panel deflections would be expected to be a function of cross section inertia as affected by skin thickness. A check of the value shown for the center panel of Panel 1 shows (Figure 14) a center deflection of 0.262 in. This compares with an 0.283-in. deflection for Panel 2 at 6-psi load at the same location. Since the major differences between Panels 1 and 2 are the number of layers (one for Panel 1 and two for Panel 2) of woven roving in the skin and the orientation of the truss core web, the lower deflection noted on Panel 1 must be attributed to the equilateral truss core arrangement. This equalateral truss core was more effective in providing a transverse support to loads than was the square arrangement Panel 2. Deflections of Panel 3 which had a thick skin (Figure 15) were greatly reduced for the same panel loading.

Figure 22 shows a comparison of measured and predicted deflections by a finite element approximation for Panel 1 at a 6-psi load. The principle of finite element analysis is to determine internal stresses for a structure from the deflections at selected nodes. The sum of the known external loads and internal "actions" due to deflection as function of element stiffness gives distribution of the moments and reactions of panel. The agreement of measured deflections and computed values give encouragement to the use of the method for future structural designs of GRP sandwich arrangements. With suitable adjustments for truss core arrangement and skin layers, similar results were obtained for Panel 2 performance.

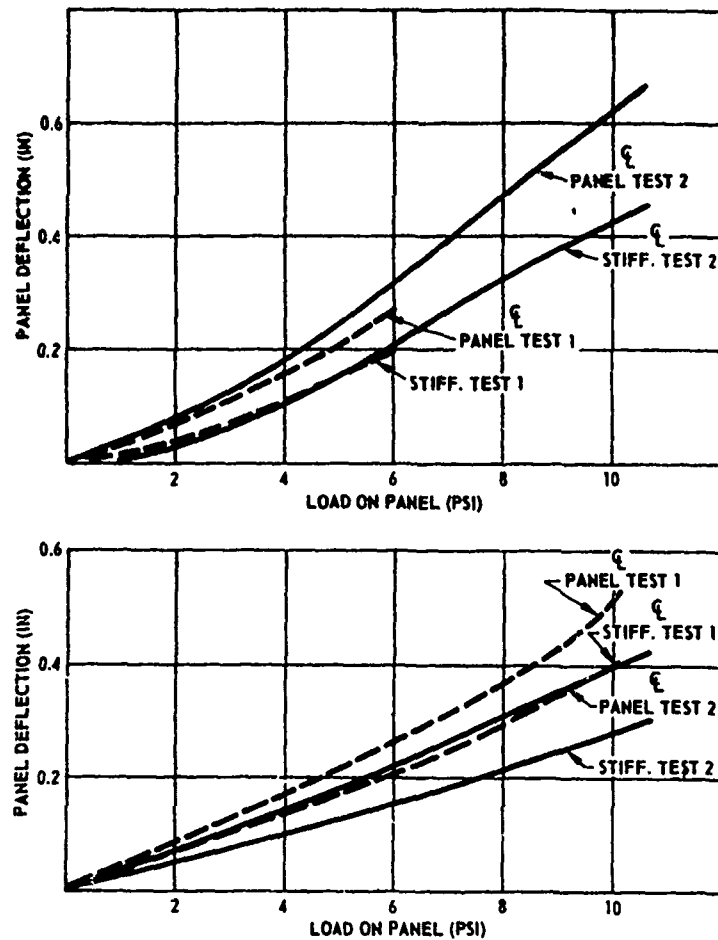


Figure 21 - Deflection Measured at the Center, Panels 1 and 2

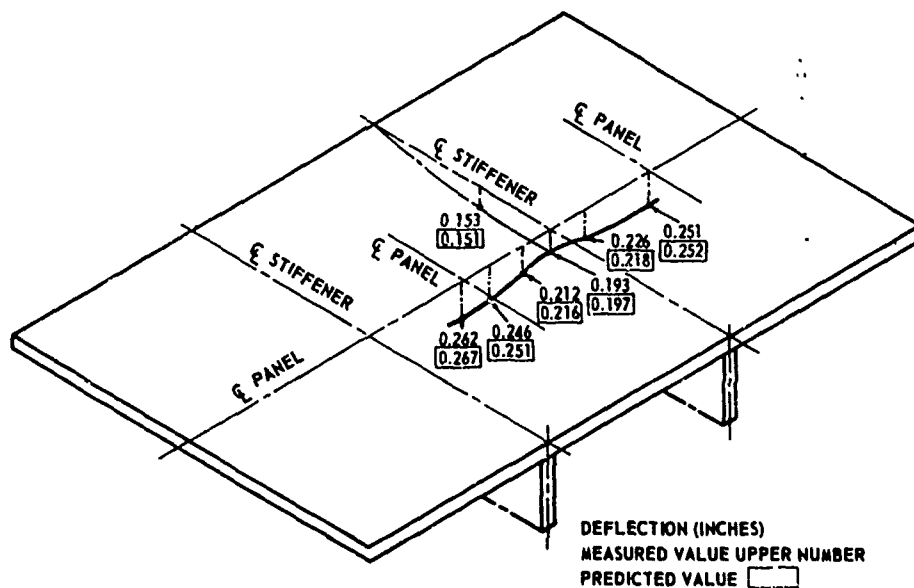


Figure 22 - Comparison of Measured and Predicted Deflections for Panel 1

The correlation between predicted and measured panel deflections indicates that panel stress prediction would be possible. Figure 23 shows a comparison of measured strain and predicted stress along the centerline of Panel 1. This plot (to scale) of strain and stress curves emphasizes some of the problems which arise limiting the number of elements that can be used in the space frame approximation (at the stiffener) and the unknown response of the sandwich panel at the fixed edge. The ratio of stresses at the panel center to the measured strain and the location of zero stress in the center panel are as expected. A much greater number of strain measurements and finite elements would be required for an exact comparison at the stiffener. The figure also indicates features which could be explored provided adequate funding is available for the additional studies.

The predicted stress and measured strain for Panel 2 on (Figure 24) were plotted to scale to show how well stress prediction corresponded to measured strains. The difference in ordinate at the center of the center panel could be due to the butt in the truss core webs at this location. The prediction is based on the same elastic modulus values for both tension and compression. The edge tensile strain (bottom) would be fairly close to the values predicted at the edges. The behavior of strain at the fixed edge was explored with additional strain gages during the retest of this panel. Additional gages were located on top of the truss core webs except for one between truss core webs at 0.5 in. off the centerline location. The strain measurements on the stiffener side of the panel on the second test essentially duplicated those of the first test except at the fixed edge. The strains on the opposite side of the panel were considerably reduced.

The additional gages at the edge of the panel raised more questions and provided no help in establishing fixidity of edge. The slope of measurements 1 in. off the centerline was less than expected and the strain at the centerline was less than that at 1 and 2 in. off the centerline location. Since the strains on the top and bottom of the panel at the center were almost equal in the first test; any membrane tension effect would be minor. Any hidden sandwich failures from the first test would have caused an increase in the strains measured in the second test, not a

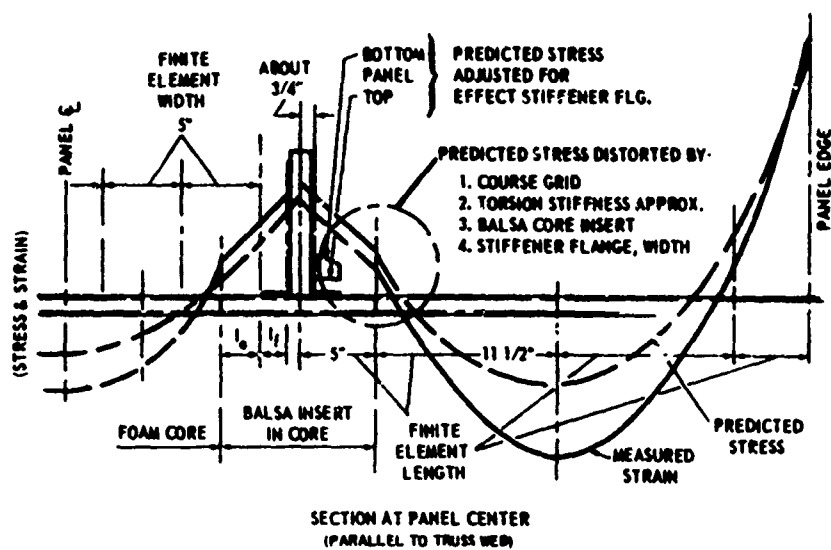


Figure 23 - Comparison of Predicted Stress and Measured Strain on Panel 1

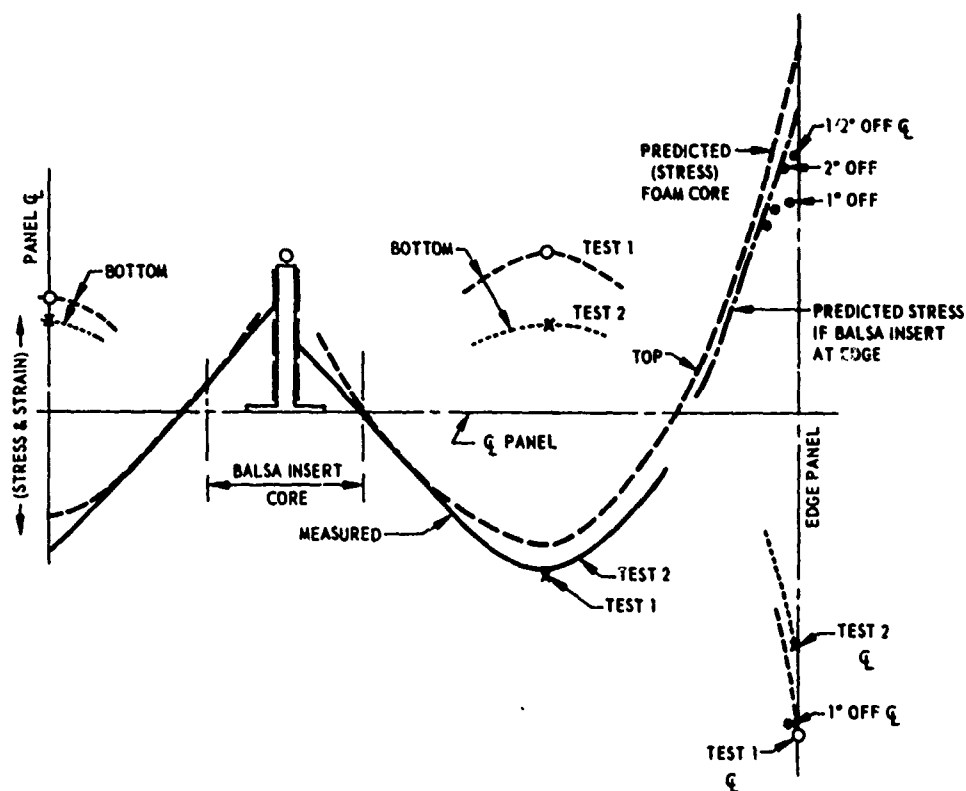


Figure 24 - Comparison of Predicted Stress and Measured Strain on Panel 2

reduction as shown for the bottom surface of the panel for the second test. The dotted line shown for the stress at the outside panel edge shows the stress prediction for a wooden insert located in core at support. If the outside plywood core insert extends into the panel, the slope of measured strain might be explained as a large change in section inertia due to the insert.

Figure 25 shows a plot of measured strain along the sides of the stiffeners at the centerline of the panels and a sample material property sensitivity evaluation on stiffener response. The stiffener response-neutral axis location is influenced by the sandwich arrangement, e.g., skin thickness and core property. Strain measurements were made to determine the influence of the sandwich design on this stiffener strength. The location of the zero strain height is necessary to calculate stiffener stress and deflection (and strain in the sandwich at the stiffener). These strain measurements are influenced by the stiffener torsion stress to some unknown degree as indicated by the strain curve, Figure 20.

The plot on the lower part of Figure 25 shows a sensitivity check of effect of bidirectional elastic modulus of the balsa core insert. The upper line represents a transverse balsa modulus equal to 0.1 of the value along the truss core direction. These properties are plotted along an effective width of sandwich on stiffener section inertia. For example, a neutral axis measured height of 1 1/2 in. for Panel 2 would correspond to about a 6 in. effective width and an "isotropic" balsa core or a full effective width (10 in.) including an orthotropic balsa property.

Figure 26, a plot of strain along top of stiffener, is included to show design features which can be obtained from tests and the effectiveness of the test fixture for this purpose. The stiffener on Panel 2 was reinforced after the first test to eliminate shear buckling and was instrumented to investigate end fixidity. The measured 10-psi panel load strains are plotted along one-half the length of the stiffener. This figure also shows a plot for a theoretical fixed-end beam bending moment under uniform load, corresponding to the ordinate of strain at the stiffener center.

The figure shows the location of the clamp frame and the first row of bolts holding the end of the stiffener. The added layers of reinforcing cloth are shown also to facilitate interpretation of the strain

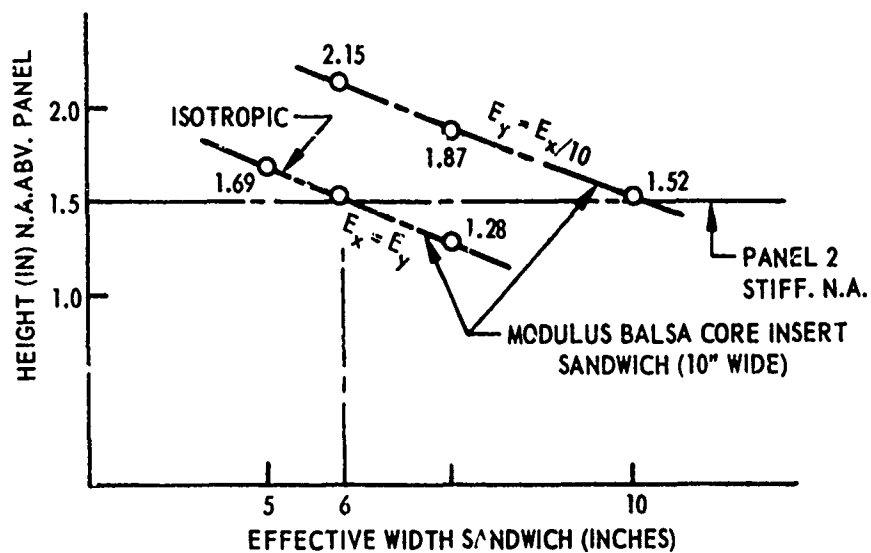
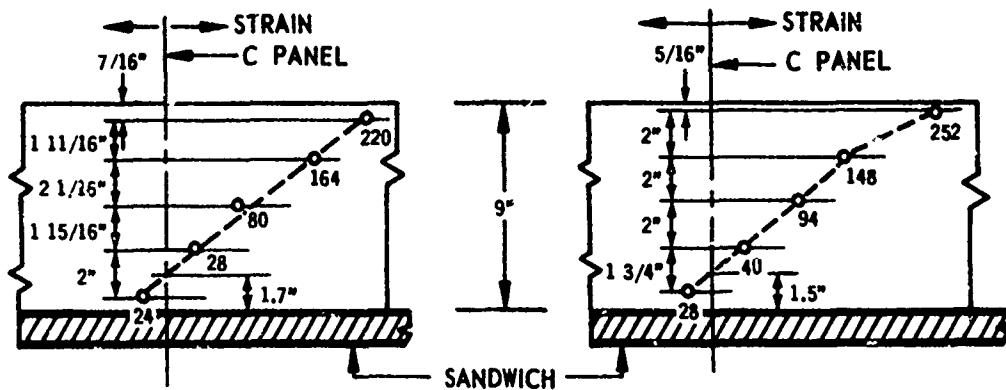


Figure 25 - Measured Strain on Stiffeners versus Neutral Axis Location

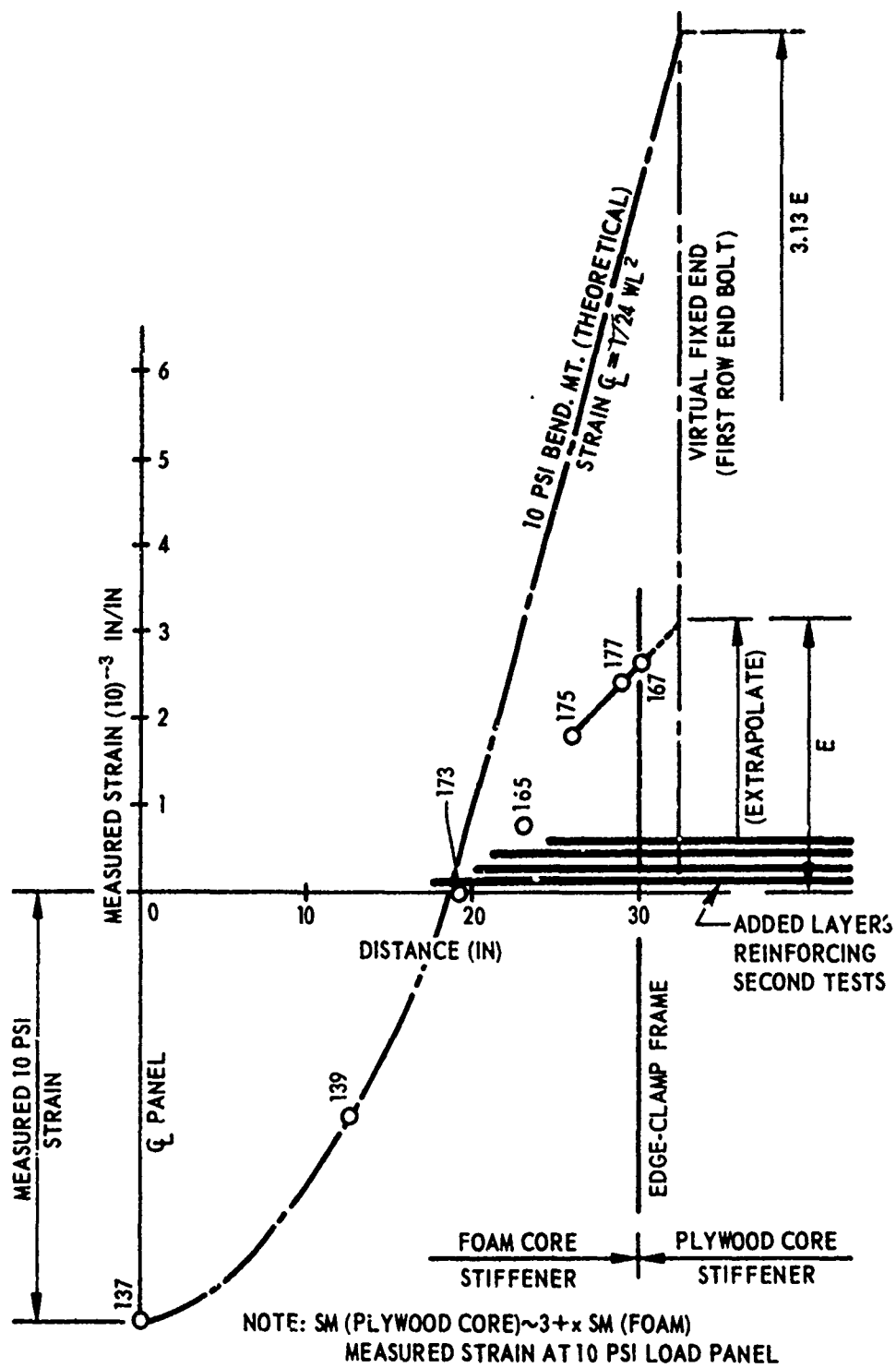


Figure 26 - Strain along the Top of the Stiffener, Modified Panel 2

values. It should be noted that the location of zero strain along the top of the stiffener corresponds reasonably well to the theoretical prediction. The low strain at the stiffener end is due to added reinforcement and to the plywood insert in the stiffeners beyond the edge clamp frame line.

If only shear buckling were involved, the skin could have been stabilized by using Unicore construction. However, the added stiffener skin double layers reduced both bending and shear stress at the fixed end of the stiffener.

CONCLUSION

These initial hydrostatic tests of three sample stiffened GRP sandwich panels serve to demonstrate a capability to obtain valuable design criteria for structural design. In particular, the tests of fixed-edge, normal-loaded, full-scale boat structures provide previously unavailable information that is absolutely essential for the rational design of GRP boat structures. If adequate funding is provided to enable an evaluation of promising alternate sandwich arrangements under static and an extension of the investigation to "dynamic" or impulse type loads, more efficient, lighter weight, high performance craft structures should be attainable.

The structural design of the U.S. Navy PCF, a 50-ft patrol craft, can be used as an example. The PCF contractor weight summary indicated that the structure was about 29 percent full load weight and almost three times the weight of the payload. The plans for the boat showed a bottom structure consisting of 1/4-in. aluminum plate supported by 2-in. stringers spaced 7 1/2 in. apart. No information was available on how these scantlings were obtained.

The weight of the PCF bottom per square foot is about 4.63 lb including the stringers. The comparable GRP sandwich Panel 1 weighs about 2 lb and has approximately the same support spacing (30 in. versus 31 in. for the PCF). Use of H.A. Schade's empirical formula for plate stress gives a 60-psi bottom load limit if the aluminum limit stress is set at 30,000 psi. However, a fixed-end beam check for the 2-in. stringer shows only 45 psi. With the addition of suitable edge doubling, the GRP panel has a potential 30-psi load capability at 21,000-psi limit stress (equivalent stress/density ratio of aluminum). Conversion of these numbers to

an efficiency (load/weight) ratio shows a 50 percent improvement for the sandwich structure. However, because there is no assurance that the boat will be handled carefully during operation, the sandwich skin should be at least doubled. This added weight of approximately 0.75 lb/ft^2 would provide the sandwich with a load capability about that of the 1/4 in. aluminum skin with a weight of about 0.6 of the PCF bottom as built. This reduced hull weight would provide options for proportionate increase of craft speed, payload, or reduced craft size.